



LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

Using the Mount Pinatubo Volcanic Eruption to
Determine Climate Sensitivity: Comments on
"Climate Forcing by the Volcanic Eruption of
Mount Pinatubo" by David H. Douglass and
Robert S. Knox

T. M. L. Wigley, C. M. Ammann, B. D. Santer, K.
E. Taylor

April 25, 2005

Geophysical Research Letters

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

**Using the Mount Pinatubo volcanic eruption to determine climate sensitivity:
Comments on “Climate forcing by the volcanic eruption of Mount Pinatubo”
by David H. Douglass and Robert S. Knox**

T.M.L. Wigley¹

C.M. Ammann¹

B.D. Santer²

K.E. Taylor²

April, 2005

Submitted to *Geophysical Research Letters*

Running Title: Mount Pinatubo

Primary Index Term: 3309 (Climatology)

**Secondary Index Terms: 1620 (Climate Dynamics)
8409 (Atmospheric Effects – VOLCANOLOGY)**

¹ National Center for Atmospheric Research. P.O. Box 3000, Boulder, CO 80307

² PCMDI, Lawrence Livermore National Laboratory, Livermore, CA 94550

Phone numbers and emails:

Wigley: 303 497 2690 [wigley@ucar.edu]

Ammann: 303 497 1705 [ammann@ucar.edu]

Santer: 905 423 3364 [santer1@llnl.gov]

Taylor: 905 423 3364 [taylor13@llnl.gov]

Corresponding author:

Tom Wigley,
wigley@ucar.edu
Fax: 303-497-1333

[1] *Douglass and Knox* [2005], hereafter referred to as *DK*, present an analysis of the observed cooling following the 1991 Mt. Pinatubo eruption and claim that these data imply a very low value for the climate sensitivity (equivalent to 0.6°C equilibrium warming for a CO_2 doubling). We show here that their analysis is flawed and their results are incorrect.

[2] We begin with a very simple analysis. If ‘S’ is the climate sensitivity ($^{\circ}\text{C}/\text{Wm}^{-2}$; *DK* use λ for the sensitivity, but λ is more commonly used as the symbol for the feedback parameter, $\lambda = 1/S$), the maximum forcing is ΔQ , and the maximum temperature reduction is ΔT , then the maximum equilibrium cooling is $\Delta T_{\text{eq}} = S\Delta Q$. Because of oceanic thermal inertia, the actual cooling in response to short-term volcanic forcing will be substantially less, by a factor α where $\alpha = \Delta T/\Delta T_{\text{eq}}$. What do *DK*’s results imply for α ? *DK* have $S = 0.15^{\circ}\text{C}/\text{Wm}^{-2}$, $\Delta Q \approx -3 \text{ Wm}^{-2}$ (this is obtained by multiplying the peak visible optical depth change of 0.16, see their Fig. 2, by a scaling factor of 18.5, their central estimate), and ΔT (for which the smoothed value is $\approx -0.5^{\circ}\text{C}$). This implies that $\alpha = \Delta T/(S\Delta Q) \approx 1.1$. (A larger cooling estimate, such as the unsmoothed value of -0.7°C , would give an even larger value for α .) *DK*’s results therefore imply that the actual cooling from the Pinatubo eruption was more than the equilibrium cooling. This is an improbable result, and it is difficult to think of a physical mechanism through which it might occur. Conventional values for α are around 0.3, so the discrepancy here is very large.

[3] We can test the validity of the *DK* approach using a model case where we know the climate sensitivity, and see whether their approach can recover the known value. The case we consider is a coupled atmosphere-ocean general circulation model simulation of the effects of volcanic eruptions on climate [*Ammann et al.*, 2003]. The model used is the NCAR/DOE Parallel

Climate Model (PCM). This is the same model that was used by *DK* to obtain the post-Pinatubo optical depth series (their Fig. 2). The Pinatubo response signal in PCM is unusually well-characterized, because multiple model realizations allow the noise of internally-generated variability to be reduced significantly (see *Wigley et al.*, 2005). We also know from earlier work [*Raper et al.*, 2001] that the climate sensitivity for this model is $0.46^{\circ}\text{C}/\text{Wm}^{-2}$, smaller than most other models but still substantially greater than the *DK* result of $0.15^{\circ}\text{C}/\text{Wm}^{-2}$.

[4] It is a simple matter to fit *DK*'s analytical solution for the Pinatubo response (their equ. 6) to the PCM results for Pinatubo. Their analytical solution contains two free parameters, the climate sensitivity (S) and a response time (τ). By minimizing the root-mean-square difference between the PCM 'observed' and *DK* 'model' values we obtain $S = 0.166^{\circ}\text{C}/\text{Wm}^{-2}$ and $\tau = 8.3$ months for PCM. This best-fit result is shown in Fig. 1. (Note that PCM's peak cooling is slightly less than the observed peak cooling.) It is clear that, while the *DK* method works for curve-fitting, it is unable to recover the known value of S for PCM, underestimating the true sensitivity by a factor of three. Given this failure, the method is unlikely to be able to estimate a reliable sensitivity value from real-world observational data.

[5] The reason for this failure lies in the one-box model that is used by *DK*. Such a model cannot, in general, adequately capture the thermal inertia effects of the ocean – to do so requires modeling the ocean more realistically. At the very least, the heat flux out of the mixed-layer into the deep ocean must be accounted for. This is a non-trivial term. To see this we write the one-box model equation in a more general form (see, e.g., *Raper et al.*, 2001):

$$C \, d\Delta T/dt + \Delta T/S = \Delta Q - \Delta F$$

where C is the heat capacity (so $\tau = CS$) and ΔF is the flux of heat at the base of the mixed layer. At the time of minimum temperature, the first term is zero and we have

$$S = \Delta T / (\Delta Q - \Delta F).$$

If ΔF is ignored, $S = \Delta T / \Delta Q$. Using the smoothed value for maximum cooling (0.5°C) and the forcing at the time of maximum cooling from *DK*'s Fig. 2 ($0.14 \times 18.5 = 2.6 \text{Wm}^{-2}$) gives $S = -0.5 / -2.6 = 0.19^\circ\text{C/Wm}^{-2}$, quite similar to the *DK* result.

[6] Now let us use the more correct expression that accounts for the heat flux at the base of the mixed layer. The observed value of ΔF at the time of maximum cooling is not known, but an approximate estimate of around -2Wm^{-2} can be obtained from the data of Levitus [2000]. It should be noted that the flux at this time is, as simple physics demands, from the deeper ocean into the mixed layer. The above flux value is consistent with values obtained from AOGCM simulations. The implied value for S then becomes approximately $0.5 / (2.6 - 2) = 0.83^\circ\text{C/Wm}^{-2}$, in accord with conventional estimates such as *Soden et al.* [2002] and *Robock* [2003], and with the results of *Wigley et al.* [2005]. The above sensitivity estimate is subject to considerable uncertainty through uncertainties in all three terms, ΔT , ΔQ and ΔF . Nevertheless, the neglect of ΔF makes a radical difference and must lead, as it does in *DK*'s analysis and in our parallel analysis of the PCM results, to a considerable underestimate of the climate sensitivity.

[7] This is not the only flaw in the *DK* analysis. For example, as explained by *Robock* [2005], *DK* appear not to understand the concept of radiative forcing. They also confuse the time

scale in their one-box model with the volcano response time (i.e., the time scale for relaxation from peak cooling back to steady state), claiming that the latter is very short, about 6.8 months. This is wrong. The box-model time scale (τ) and the volcano response time (τ_v) are two different things. We can illustrate this using the PCM results from Fig. 1. In this case, the value of τ that is used is 8.3 months. Fitting an exponential decay to the ‘tail’ of the temperature response curve (e.g., for times greater than 20 months) gives an e-folding time of about 15 months. In work using a more realistic model, *Wigley et al.* [2005] obtain even larger values for τ_v , and the reality of a long volcano response time is supported by numerous other studies [e.g. Free and Angell, 2000; Santer et al., 2001; Gillett et al., 2004]. τ_v is clearly different from τ .

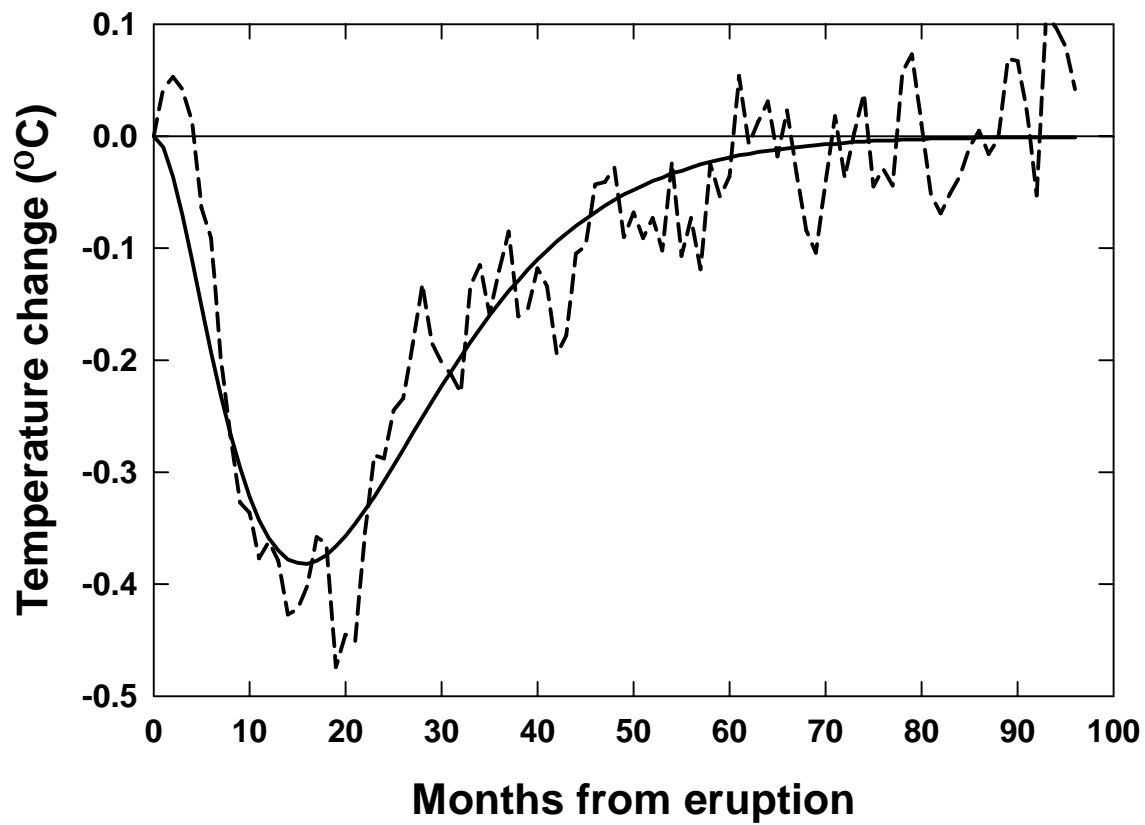
[8] *DK* suggest that other analyses are flawed because they have assumed values of τ_v that are too large. This, too, is incorrect. For example, in *Wigley et al.* [2005], τ_v values are obtained by statistical fits to either observed or model-generated data. No *a priori* assumptions are made regarding the magnitude of τ_v . Of course, no such assumptions are made in other modeling studies either, such as those of *Ammann et al.* [2003] and *Soden et al.* [2002]. The volcano response time is generated internally by model physics.

[9] In conclusion, neither the physics nor the results in the *DK* paper are correct. Their unconventional result that the climate sensitivity is very low is simply an artifact of their use of an over-simplified model to fit the observed cooling from Pinatubo.

Acknowledgments. We thank Alan Robock and Brian Soden for helpful comments on the manuscript. NCAR is sponsored by the National Science Foundation.

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

Fig. 1: Simulation of the response to the Mt. Pinatubo eruption from PCM (average of 16 realizations, dashed line) compared with an empirical fit using the *DK* method. Although the fit is good, the implied sensitivity and response time values are unrealistic.



References

- Ammann, C.M., G.A. Meehl, and W.M. Washington (2003), A monthly and latitudinally varying forcing data set in simulations of the 20th century climate, *Geophys. Res. Lett.*, *30*, 1657, doi:10.1029/2003GL016875.
- Douglass, D. H., and R. S. Knox (2005), Climate forcing by the volcanic eruption of Mount Pinatubo, *Geophys. Res. Lett.*, *32*, L05710, doi:10.1029/2004GL022119.
- Free, M., and J.K. Angell (2002), Effect of volcanoes on the vertical temperature profile in radiosonde data. *J. Geophys. Res.*, *107*, doi:10.1029/2001JD001128.
- Gillett, N.P., A.J. Weaver, F.W. Zwiers, and M.F. Wehner (2004), Detection of volcanic influence on global precipitation. *Geophys. Res. Lett.*, *31*, doi:10.1029/2004GL020044.
- Levitus, S., J.I. Antonov, T.P. Boyer, and C. Stephens (2000), Warming of the world ocean, *Science*, *292*, 267–270.
- Raper, S.C.B., J.M. Gregory, and T.J. Osborn (2001), Use of an upwelling-diffusion energy balance climate model to simulate and diagnose A/OGCM results, *Climate Dynamics*, *17*, 601–613.
- Robock, A. (2003), Introduction: Mount Pinatubo as a test of climate feedback mechanisms. in *Volcanism and the Earth's Atmosphere*, A. Robock and C. Oppenheimer, Eds., Geophysical Monograph 139, American Geophysical Union, Washington, DC, 1–8.
- Robock, A. (2005), Using the Mount Pinatubo volcanic eruption to determine climate sensitivity: Comments on “Climate forcing by the volcanic eruption of Mount Pinatubo” by David H. Douglass and Robert S. Knox, *Geophys. Res. Lett.* (submitted).
- Santer, B.D., *et al.* (2001) Accounting for the effects of volcanoes and ENSO in comparisons of modeled and observed temperature trends. *J. Geophys. Res.*, *106*, 28033-28059.

Soden, B. J., R. T. Wetherald, G. L. Stenchikov, and A. Robock (2002), Global cooling following the eruption of Mt. Pinatubo: A test of climate feedback by water vapor. *Science*, 296, 727–730.

Wigley, T. M. L., C. M. Ammann, B. D. Santer, and S. C. B. Raper (2005), The effect of climate sensitivity on the response to volcanic forcing, *J. Geophys. Res.*, 110, doi:10.1029/2004JD005557, in press.